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In light of this need a major part of our research program in the last year has been the continuation of research into the semiconductor-doped glass material system. Bulk DFWM an photoluminescence experiments on these materials determined that they have a large nonlinear index of refraction ( $n_2$  approx  $10^{-14}$  m<sup>2</sup>/w) with fast response times ( $\tau$  less than 16 psec) required for high speed optical signal processing. Along with collaborators in the University of Glasgow we successfully developed a successful ion-exchange (Na:K) technique for producing low-loss optical waveguides in these materials, the details of which are in the enclosed reprint.

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## SIGNAL PROCESSING WITH DEGENERATE FOUR-WAVE MIXING

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Principal Investigator:

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The enclosed reprints and preprints represent work carried out by personnel supported under this contract. Summaries of this work along with other work performed but not as yet, published are contained within this report.

We (Stegeman and Seaton) were invited to produce a review paper on Degenerate Four-Wave Mixing<sup>1</sup> with guided waves which was published in a special issue of IEEE Journal of Quantum Electronics. One of the conclusions of that review was the need development and understanding of new nonlinear optical materials suitable for nonlinear guided wave devices.

In light of this need a major part of our research program in the last year has been the continuation of research into the semiconductor-doped glass material system. Bulk DFWM and photoluminescence<sup>2</sup> experiments on these materials determined that they have a large nonlinear index of refraction ( $n_2 \sim 10^{-14} \text{ m}^2/\text{w}$ ) with fast response times ( $\tau < 16 \text{ psec}$ ) required for high speed optical signal processing. Along with collaborators in the University of Glasgow we successfully developed a successful ion-exchange ( $\text{Na}^+:\text{K}^+$ ) technique for producing low-loss optical waveguides in these materials, the details of which are in the enclosed reprint.<sup>3</sup>

We have been studying the effects of incorporating "real" material parameters into the operation of nonlinear optical waveguide devices<sup>4</sup> and have determined that the most important parameter for guided wave devices is  $\Delta n_{\text{sat}}$  ie. the maximum change in refractive index which can be induced in a material before saturation effects set in. To determine this parameter (which has not previously been studied) we have been performing bulk DFWM experiments in a number of semiconductor-doped glass samples. By plotting DFWM reflectivity against pump intensity we observe signal saturation over a range of samples at  $\sim 1 \text{ MW/cm}^2$  intensity levels. Using both a two-level atom saturation model and on exponential decay model we determined  $\Delta n_{\text{sat}}$  of  $1.7 \times 10^{-4}$  and  $1.13 \times 10^{-4}$  respectively. Experiments are underway to determine the origin of "permanent" gratings which appear to be created via a photo darkening effect in the semiconductor glasses. This effect appears to be particularly prevalent in the Schott soda-lime glasses which we specially obtained to facilitate the ion-exchange process. The problem of "solarization" ie. photo-darkening is known to be particularly prevalent in soda-lime based glasses so color filter samples with borosilicate host glasses (ie. BK7 or standard Corning filters) will be further investigated for ion-exchangability.



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Other work which has been performed with AFOSR support from this contract has been of a theoretical nature regarding nonlinear guided wave (NLGW) structures where the nonlinearity is sufficiently large to effect the guided wave field distribution. We have demonstrated numerically the efficient excitation of stable  $TE_0$  NLGW's with a suitably chosen gaussian input beam. Selective excitation of any of three possible field distributions corresponding to the same flux level in a system comprising a linear thin film waveguide bounded by two nonlinear, self-focussing media was demonstrated numerically.<sup>5</sup>

We also observed that external excitation of a NLGW can produce sequential threshold behaviour through multi-soliton emission from the nonlinear waveguide.<sup>6</sup> This effect has intriguing consequences for original optical switching devices.

## References

1. "Degenerate four-wave mixing with guided waves," G. I. Stegeman, C. T. Seaton, and C. Karaguleff, IEEE J. Quant. Elec., QE-22, 1344 (1986) Invited Paper.\*
2. "Ultrafast carrier and grating lifetimes in semiconductor-doped glasses," S. S. Yao, C. Karaguleff, A. Gabel, R. Fortenberry, C. T. Seaton, and G. I. Stegeman, Appl. Phys. Letts., 46, 801 (1985).
3. "Semiconductor-doped glass ion-exchanged waveguides," T. J. Cullen, C. N. Ironside, C. T. Seaton, and G. I. Stegeman, Appl. Phys. Letts., 49, 1403 (1986).\*
4. "Effects of saturation and loss on nonlinear directional couplers," G. I. Stegeman, C. T. Seaton, C. N. Ironside, T. J. Cullen, and A. C. Walker, Appl. Phys. Letts. (in press).
5. "Gaussian beam excitation of  $TE_0$  nonlinear guided waves," E. M. Wright, G. I. Stegeman, C. T. Seaton, and J. V. Moloney, Appl. Phys. Letts. 49, 435 (1986).\*
6. "Multi-soliton emission from a nonlinear waveguide," E. M. Wright, G. I. Stegeman, C. T. Seaton, J. V. Moloney, and A. D. Boardman, Phys. Rev. A 34, 4442 (1986).\*

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# Degenerate Four-Wave Mixing with Guided Waves

AFOSR-TR-87-0548

GEORGE I. STEGEMAN, COLIN T. SEATON, AND C. KARAGULEFF

(Invited Paper)

**Abstract**—The theory, experimental implementation, and applications of degenerate four-wave mixing with guided waves are reviewed.

## I. INTRODUCTION

**D**EGENERATE four-wave mixing (DFWM) has been studied extensively in bulk media for a number of years, and many applications have been predicted and demonstrated [1]. In the most general interaction geometry, there are three input beams, two of which are counterpropagating and a third signal beam incident at an arbitrary angle, all of which interact to generate a fourth wave via the third-order susceptibility of the medium. The process is automatically phase matched and the conjugate beam is emitted back along the direction of the incident signal beam. The efficiency of the process is proportional to the product of the two pump beams, the length of the interaction region along the direction of the conjugate beam, and the magnitude of the nonlinear susceptibility.

The electromagnetic waves guided by the interface between two semi-infinite media, by single or multiple films bounded by two semi-infinite media, or by fibers can be used to implement DFWM. The key feature introduced by guided waves is that the fields decay exponentially away from the boundaries into the semi-infinite bounding media with  $1/e$  distances of typically a fraction of the wavelength of the radiation being guided. Therefore, the effective beam dimension along the direction normal to the surface can be on the order of the wavelength of light, which corresponds to the minimum beam cross-sectional area and hence maximum power density for a given input power level. Furthermore, these high fields can be maintained for long propagation distances, centimeters in the case of thin-film or channel waveguides, and meters or kilometers for optical fibers. Thus, the high fields and long phase-match distances required for efficient interactions can be achieved with modest or low total powers. These attractive features were recognized at an early stage and have, by now, been applied to an impressive number of nonlinear guided wave phenomena [2].

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Guided waves, in general, result from a coupling between an electromagnetic wave and some resonance. The resonances can be geometric, for example, as occurs in a fiber (or thin-film) waveguide [3], [4] where constructive interferences across the core or film result in waveguide modes. The resonances can also be material properties related. For example, the plasma resonance associated with the electron gas in a metal is coupled to an electromagnetic field via the interaction between the field and the charges and leads to surface plasmons [5]. Such material resonances are usually accompanied by losses and there is always a tradeoff between the propagation distance and the field confinement [6]. For this reason, most work in guided wave nonlinear optics for device applications has been limited to dielectric waveguides with freely propagating guided waves.

The first experiments reported [7] on waveguide DFWM were performed in  $\text{CS}_2$  filled fibers in which the long interaction distance was more than enough to compensate for the small nonlinearity associated with  $\text{CS}_2$ . The phase conjugate properties of the interaction were demonstrated. Despite promising applications [8] such as wide-angle narrow-band filtering, image-frequency conversion, and small-sample spectroscopy, there has been little progress in phase conjugation in fibers since about 1980. Recent interest has centered on experiments in planar geometries; specifically, experiments using thin-film guided waves [9] and surface plasmons [10] were reported. Because of the potential applications to "real-time" signal processing [2], [10], these initial experiments represent the first steps in a field which should develop rapidly over the coming years.

In this paper, we review progress in degenerate four-wave mixing with guided waves. Although the emphasis is on experimental results, the basic formulation of the problem and its applications will also be discussed.

## II. THEORETICAL FORMULATION

Degenerate four-wave mixing can be carried out with either two or four beams guided. Certainly, the most efficient interactions occur with all four waves guided since this configuration optimizes the power density in each wave for a given power. For the two-wave guided case, two externally incident waves can be used to phase conjugate a guided wave [12], or two guided waves can be used to phase conjugate an externally incident plane wave field [13]. Here we consider only the four guided wave case.

### A. Guided Waves

Guided waves are electromagnetic fields which satisfy both Maxwell's equations in every medium into which the fields penetrate and continuity of the tangential boundary conditions at every interface. For the simplest case of isotropic waveguide media with propagation along the  $x$  axis, the  $s$ th input wave ( $s = 1, 2, 3$ ) in the  $m$ th normal mode can be written as

$$E(r, t) = \frac{1}{2} E^{(m,s)}(r) a^{(m,s)}(x) \cdot \exp [i(\omega t - \beta^{(m,s)} k_r \cdot r)] + \text{c.c.} \quad (1)$$

where  $\beta^{(m,s)}$  is the effective index obtained from the solution of the appropriate dispersion relation and  $E^{(m,s)}(r)$  is the corresponding normal mode field. Since these solutions are normal modes, they satisfy the orthogonality relations

$$\int_{-\infty}^{\infty} dr_{\perp} E^{(m)}(r) \cdot E^{(n)*}(r) = A_{m,n}^2 \delta_{m,n} \quad (2)$$

where the vector  $r_{\perp}$  is orthogonal to the propagation direction defined by  $k$  and  $A_{m,n}$  is the normalization constant chosen so that  $|a^{(m)}(x)|^2$  is the guided wave power for two-dimensional waveguides or the guided wave power per meter of wavefront for planar guided waves. These expressions are valid for all guided wave fields, fibers, channel waveguides, surface plasmon waves, etc.

The mixing of three input guided waves leads to nonlinear polarization fields which are usually expanded in products of the mixing fields. A nonlinear polarization field of frequency  $\omega$  is generated in each of the media in which the guided wave fields exist. It is usually written as

$$P_{(r,t)}^{NL} = \frac{1}{2} P_{(r)}^{NL} \exp [i(\omega t - \beta_p k_p x)] + \text{c.c.} \quad (3)$$

where  $\beta_p k_p$  is the polarization wavevector. The generation of the nonlinearly produced conjugate wave can be treated in the slowly varying amplitude approximation using well-known guided wave coupled mode theory [3], [4] with the result that, for propagation along the  $x$  axis,

$$\frac{d}{dx} a^{(n,s)}(x) = i \frac{\omega \mu_0 c}{2 \beta^{(n,s)} A_{n,n}^2} \int_{-\infty}^{\infty} dr_{\perp} P_{(r)}^{NL} \cdot E^{*(n,s)}(r) \cdot \exp [-i(\beta_p - \beta^{(n,s)})x]. \quad (4)$$

For a fiber or a channel waveguide, the integral is taken over the cross-sectional area, and in the case of planar waveguides, the integral is performed over the depth coordinate.

### B. Degenerate Four-Wave Mixing in Guided Wave Geometries

The same formalism can be used to discuss the four-wave mixing in one- and two-dimensional waveguides [8], [14]. There are three input beams with wavevector  $[\beta^{(m,1)} k_1]$ ,  $[\beta^{(m,2)} k_2]$ , and  $[\beta^{(m',3)} k_3]$  and one output beam

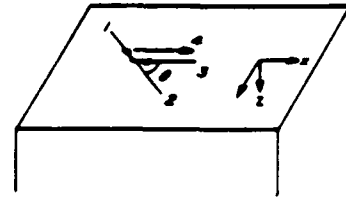


Fig. 1. The planar four-wave mixing geometry discussed in this paper. The pump beams are 1 and 2, the signal wave is 3, and the conjugate wave is 4 [14].

with wavevector  $[\beta^{(n,4)} k_4]$  as shown in Fig. 1 for a planar guided wave geometry. Wavevector conservation is given by

$$\beta^{(m,1)} k_1 + \beta^{(m',2)} k_2 + \beta^{(m',3)} k_3 + \beta^{(n,4)} k_4 = 0 \quad (5)$$

with  $k_1 = k_2 = k_3 = k_4$ . If the two input beams 1 and 2 are exactly contradiagonal and have the same mode number  $m = m'$ ,  $\beta^{(m,1)} k_1 = -\beta^{(m,2)} k_2$ . Therefore, it is necessary that  $m'' = n$  so that  $\beta^{(n,4)} k_4 = -\beta^{(n,3)} k_3$ , and signal beam 4 is generated backwards along the direction of incidence of beam 3, independent of the incidence direction of beam 3. (For a fiber, all four beams propagate along the fiber axis.) Note that this process does require that beams 1 and 2 have the same mode order  $m$ , that beam 4 is radiated into the same mode index  $n$  as beam 3, and  $m$  and  $n$  are not necessarily equal [14]. Because there are multiple guided wave solutions associated with the same guided wave polarization characteristics, the spectrum of possible interactions is larger than that for plane waves. (The other consequence is that the possible directions of the incident waves are restricted to one (fiber or channel waveguide) or two (planar waveguide) dimensions for an all-guided wave interaction.)

For an isotropic material, the conjugate polarization term [14] is given by

$$P^{NL}(r) = [4\epsilon_0 \chi_{1122}^{(3)}(-\omega, \omega, -\omega, \omega) \cdot E_i^{*(n,3)}(r) E_j^{(m,2)}(r) E_j^{(m,1)}(r) + 2\epsilon_0 \chi_{1221}^{(3)}(-\omega, \omega, -\omega, \omega) E_i^{(m,1)}(r) \cdot E_j^{(m,2)}(r) E_j^{*(n,3)}(r)] a_1(x) a_2(x) a_3^*(x) \quad (6)$$

where the notation for the field amplitudes has been simplified so that  $a_1(x) = a^{(n,1)}(x)$ . This expression simplifies far from any resonant behavior in the  $\chi^{(3)}$  terms and  $\chi_{1122}^{(3)} = \chi_{1221}^{(3)} = \chi_{\text{eff}}^{(3)}$ . For guided wave fields,

$$P^{NL}(r) = 2c\epsilon_0 n_{\gamma}^2 n_{2\gamma} \{ \frac{1}{2} E_{\gamma i}^{*(n,3)}(r) E_{\gamma j}^{(m,1)}(r) E_{\gamma j}^{(m,2)}(r) + \frac{1}{2} E_{\gamma j}^{*(n,3)}(r) E_{\gamma j}^{(m,2)}(r) E_{\gamma i}^{(m,1)}(r) \} \cdot a_1(x) a_2(x) a_3^*(x) \quad (7)$$

in each medium (labeled  $\gamma$ ) where  $n_{2\gamma} \neq 0$ . Here we have defined  $3\chi_{\text{eff}}^{(3)} = n_{2\gamma} n_{\gamma}^2 \epsilon_0 c^2$  where  $n_{2\gamma}$  is the intensity-dependent refractive index for the  $\gamma$ th medium. Clearly, similar equations can be derived for the nonlinear polarizations driving the pump and signal beams.

Here we consider only the two cases which have been studied experimentally. For fibers or channel waveguides, the coupled mode equations are

$$\frac{d}{dx} a_4(x) = i(\kappa_{1122} + \kappa_{1221}) a_3^*(x) a_2(x) a_1(x) \quad (8a)$$

$$\frac{d}{dx} a_3(x) = -i(\kappa_{1122} + \kappa_{1221}) a_4^*(x) a_1(x) a_2(x) \quad (8b)$$

with

$$\kappa_{1122} = \frac{2\omega\epsilon_0}{3A_{n,n}^2\beta} \int_{-\infty}^{\infty} dr_{\gamma} n_{\gamma}^2 n_{2\gamma} [E_{\gamma i}^{*(n,4)}(r) E_{\gamma i}^{*(n,3)}(r) \cdot E_{\gamma j}^{(m,1)}(r) E_{\gamma j}^{(m,2)}(r)] \quad (9a)$$

$$\kappa_{1221} = \frac{\omega\epsilon_0}{3A_{n,n}^2\beta} \int_{-\infty}^{\infty} dr_{\gamma} n_{\gamma}^2 n_{2\gamma} [E_{\gamma i}^{*(n,4)}(r) E_{\gamma j}^{*(n,3)}(r) \cdot E_{\gamma i}^{(m,1)}(r) E_{\gamma j}^{(m,2)}(r)]. \quad (9b)$$

In the weakly guiding case, that is, one in which the index difference across the core-cladding interface for fibers or across the channel-bounding media interfaces is small,  $\kappa_{1221} \approx \kappa_{1122}$  and (8) simplify to the well-known equations for four-wave mixing with plane waves with, of course,  $\kappa_{1122}$  given by the "overlap integrals." In the absence of pump depletion with the boundary conditions  $a_3(0) = a_1$  and  $a_4(L) = 0$  where  $L$  is the length of the interaction region, the results are

$$a_3(x) = a_1 \left[ \tan \frac{L}{l_{cr}} \sin \frac{x}{l_{cr}} + \cos \frac{x}{l_{cr}} \right] \quad (10a)$$

$$a_4(x) = ia_1^* \left[ \tan \frac{L}{l_{cr}} \cos \frac{x}{l_{cr}} - \sin \frac{x}{l_{cr}} \right] \quad (10b)$$

$$\frac{1}{l_{cr}} = (\kappa_{1122} + \kappa_{1221}) a_1(0) a_2(0). \quad (11)$$

Consider also the case of waves guided by planar surfaces. Assuming that TE beams 1 and 2 propagate along  $x'$  which is oriented at an angle  $\theta$  to the  $x$  axis along which TE beams 3 and 4 are traveling,

$$E^{(n,1 \text{ or } 2)}(r') = E^{(n,1)}(r') [\sin \theta, \cos \theta, 0];$$

$$E^{(n,3 \text{ or } 4)}(r) = E^{(n,3)}(r) [0, 1, 0]. \quad (12)$$

Again, in the limit of no attenuation or depletion for the input beams, and assuming that beams 1, 2, and 3 are introduced into the interaction region at  $x' = 0$ ,  $x' = L'$ , and  $x = L$ , respectively, substituting into (8), and integrating the signal beam from  $0 \rightarrow L$  gives the same form as (10) and (11), but with

$$\kappa_{1122} + \kappa_{1221} = \frac{\omega\epsilon_0}{3A_{n,n}^2\beta^{(n)}} (2 + \cos^2 \theta) \cdot \int_{-\infty}^{\infty} dz n_{\gamma}(z)^2 n_{2\gamma}(z) \cdot [E_{\gamma}^{(n,1)}(z) E_{\gamma}^{(n,2)}(z) E_{\gamma}^{*(n,3)}(z) E_{\gamma}^{*(n,4)}(z)]. \quad (13)$$

In the general case, it is necessary to take incident beam depletion into account which leads to a series of coupled mode equations between the amplitudes of the various beams.

### III. EXPERIMENTS IN FIBERS

In 1975, Yariv [15] suggested using nonlinear mixing as a means of compensating for phase aberrations incurred in transmitting an image down an optical fiber. He subsequently pointed out the possibility of performing this phase conjugation by degenerate four-wave mixing in a multimode waveguide [16] and suggested using a hollow core fiber filled with  $\text{CS}_2$  as the nonlinear mixing medium. Experiments based on this idea were reviewed by Hellwarth in 1982 [17], and to our knowledge, there have been no further results published since then. Thus, the only experiments to have been done are those of Jensen and Hellwarth [7] and Au Yueng *et al.* [18] in  $\text{CS}_2$  filled fibers. The first authors achieved high-fidelity conjugation with multimode pump waves using a  $Q$ -switched ruby laser and achieved DFWM reflection efficiencies of  $\approx 50$  percent for 35 kW peak pump beam powers. They also demonstrated that the wave being conjugated could serve simultaneously as its own pump wave. Au Yueng *et al.* [18] used single-mode pump waves to obtain 0.45 percent DFWM conversion efficiency for only 6 mW of CW pump power from an argon ion laser. However, the phase conjugate nature of the DFWM signal was not ascertained.

In related experiments, image transmission through a multimode optical fiber has been demonstrated [19] by using a photorefractive  $\text{BaTiO}_3$  crystal to correct for modal distortions external to the fiber. Stimulated Raman [19] and Brillouin [20] scattering in fibers can also be used to achieve phase conjugation, but these topics are outside the scope of this paper.

### IV. EXPERIMENTS WITH PLANAR GUIDED WAVES

Two experiments on four-wave mixing in integrated optics waveguides have been reported to date [9], [21]. The first deals with optically induced damage in lithium niobate waveguides [21]. A TE guided wave was created due to stray scattering via the photorefractive effect, and the mixing of the incident TM wave with this TE light creates a grating which further enhances the  $\text{TM} \rightarrow \text{TE}$  conversion. Since the gratings formed are written more or less permanently into the waveguide, this does not correspond to the usual four-wave mixing phenomenon. The characteristic time scale was typically seconds.

The second experiment was performed using freely propagating guided waves [9]. The nonlinear medium  $\text{CS}_2$ , which was used as a cladding on top of a thin-film waveguide, was located inside a cell optically contacted to the surface of a thin-film glass waveguide, as shown in Fig. 2. Three coupling prisms were required for the four beams needed in the interaction, leading to very difficult alignment problems. Since the nonlinear mixing occurred via the evanescent tails of the three incident guided waves and because the nonlinearity of  $\text{CS}_2$  is small ( $n_2 \approx 3 \times 10^{-18} \text{ m}^2/\text{W}$ ), the reflectivity (fractional conversion of



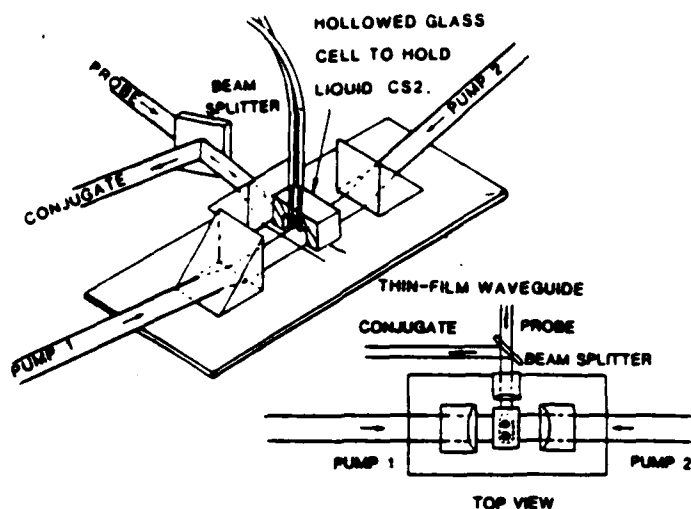


Fig. 2. Sample and coupling geometry for degenerate four-wave mixing in a thin-film waveguide showing the thin-film waveguide (Corning 7059 sputtered onto a glass microscope slide), the arrangement of high-index coupling prisms, and the glass cell for holding the  $\text{CS}_2$ . The probe beam intersects the pump beams at  $90^\circ$  under the liquid cell [9].

beam 3 into beam 4) was only  $\approx 10^{-9}$ . Nevertheless, the cubic dependence of the four-wave mixing signal was verified experimentally for 15 ns long pulses from a Q-switched, frequency-doubled Nd:YAG laser. The observed signal was consistent with calculations based on the reorientational nonlinear mechanism.

#### V. PLANAR WAVEGUIDE APPLICATIONS

This interaction has some possible applications to real-time all-optical signal processing [11], two of which, convolution and time inversion, are illustrated in Fig. 3. The two input signals to be convolved are beams 1 and 2 which have pulse envelopes  $U_1(t - x/v)$  and  $U_2(t + x/v)$ . Whether the convolution process occurs or not can be controlled by beam 3 which is assumed to have a constant amplitude during the overlap of pulses 1 and 2 inside the waveguide. Assuming that  $\theta = \pi/2$  for this case (geometry in Fig. 1) and that  $L$  is small relative to the characteristic pulse size (to preserve detail in the convolved signal), the fourth beam signal radiated is directly proportional to the instantaneous overlap of beams 1 and 2. Mathematically, the time evolution of the signal beam can be written as  $U_4(t) \propto \int U_1(t - \tau) U_2(\tau) U_3 d\tau$  where it has been explicitly assumed that the control beam is "turned on." For this application, the input signal length cannot be larger than the waveguide dimension which limits the process to pulses of 100 ps or less. Note also the time compression by a factor of two.

Another potential application of four-wave mixing to real-time processing is time reversal of an optical waveform, as illustrated in Fig. 3(b). Here  $\theta = 0$  and beams 1 and 2 are the waveform to be reversed and a control beam of constant amplitude, respectively. Beam 3 is a  $\delta$  function in time (very short pulse) and 4 is the time reversed signal. A crucial factor is that beams 1 and 3 can be propagated in different modes. If the mode number of beam 3 is larger than that of beam 1, beam 3 can overtake beam 1 from "behind." Thus, beam 4 is "read out" from

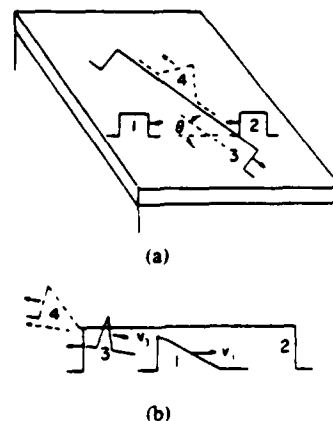


Fig. 3. The application of four-wave mixing to (a) convolution (of waveforms 1 and 2) and (b) time inversion (of pulse 1) [11].

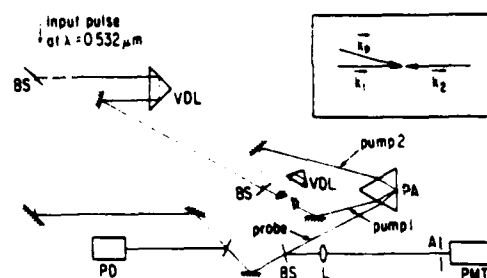


Fig. 4. Experimental setup used for the observation of optical phase conjugation with surface plasmons. The inset shows the wavevectors of the three incoming waves in the plane of the interface. (BS: beam splitters, VDL: variable delay lines, PA: prism-silver film assembly mounted on a rotary table, L: 1 m focal length lens, A: 0.5 mm diameter aperture, PMT: photomultiplier tube, PD: photodiode [10].)

trailing edge to leading edge, which corresponds to time reversal of the pulse envelope.

#### VI. SURFACE PLASMON EXPERIMENTS

A variety of experiments have been carried out by Nunzi and Ricard [10] on phase conjugation with surface plasmons in attenuated total reflection (ATR) geometries. In the visible and near infrared, the propagation distance for surface plasmons is typically tens of micrometers and the nonlinear mixing takes place under a single coupling prism.

In the first set of experiments, three incident beams were coupled into surface plasmon modes as shown in Fig. 4 and the conjugate beam was sampled via a beam splitter. For a silver film on a glass prism probed in the Kretschmann geometry, the four-wave mixing signal observed was due to heating of the metal film. This was verified by pump-probe experiments on the large spacing nonlinearly produced grating. With pulses 28 ps long, 0.6 ns decay times were measured, in good agreement with calculations. When liquid ethanol was placed between the coupling prism and the silver film, thermal gratings were formed in both the liquid and metal, and interference effects were observed. The conjugate reflectivity in these experiments was on the order of  $10^{-4}$ . This case has been analyzed not only by the experimental group [10], but also by Ujihara for nonlinearity in the dielectric medium [22] and in metal [23] (modeled as a free electron gas).

In the second set of experiments, two counterpropagating surface plasmons were excited under a coupling prism to produce a refractive index grating. This grating was then used to couple in a third wave, incident from the air side of the metal film, into a surface plasmon mode. The nonlinearly in-coupled surface plasmon was observed when it was coupled out by the prism. The mixing of the two counterpropagating surface plasmon modes was also found to generate high-frequency acoustic waves.

There has been some speculation that the efficiency of DWFM by surface plasmon could be increased by using the long-range mode guided by metal films of thickness on the order of the optical field skin depth [6], [14]. Although it appears theoretically that the efficiencies should be larger [6], [14], it has been argued by Nunzi and Ricard [10] that using such thin films would not eliminate the heating effects which dominated their experiment.

## VII. SUMMARY

The single factor which has held back the development of degenerate four-wave mixing in guided wave structures has been the lack of nonlinear materials suitable for fabrication in waveguide form. In the last few years, a number of new material systems have been identified which can be fabricated into thin film, and probably fiber form. They are essentially semiconductor-[24]-[27] and metal-doped [28] glasses and thin organic films [29]. All of these materials have very fast relaxation times, with the semiconductor glasses being the slowest with response times (electronic) of tens of picoseconds. At the present, the semiconductor-doped glasses are the only ones with sufficient nonlinearity to result in waveguide four-wave mixing with subwatt peak power levels. However, improvements are expected in the field of nonlinear organic materials so that they become competitive with the doped glass materials.

With such highly nonlinear and ultrafast materials, some of the promising applications to all-optical signal processing should become feasible, and we look forward to these possibilities with great anticipation.

## REFERENCES

- [1] Numerous chapters in R. A. Fisher, Ed., *Optical Phase Conjugation*. New York: Academic, 1982.
- [2] G. I. Stegeman and C. T. Seaton, "Nonlinear integrated optics," *Appl. Phys. Rev.*, Dec. 15, 1985.
- [3] D. Marcuse, *Theory of Dielectric Waveguides*. New York: Academic, 1974.
- [4] H. Kogelnik, in T. Tamir, Ed., *Integrated Optics, Vol. 7 of Topics in Applied Physics*. New York: Springer-Verlag, 1975, pp. 66-79.
- [5] R. H. Ritchie, "Surface plasmons in solids," *Surface Sci.*, vol. 34, pp. 1-19, 1973.
- [6] G. I. Stegeman, J. J. Burke, and D. G. Hall, "Nonlinear optics of long range surface plasmons," *Appl. Phys. Lett.*, vol. 41, pp. 906-908, 1982.
- [7] S. M. Jensen and R. W. Hellwarth, "Generation of time-reversed waves by nonlinear refraction in a waveguide," *Appl. Phys. Lett.*, vol. 33, pp. 404-405, 1978.
- [8] R. W. Hellwarth, "Theory of phase-conjugation by four-wave mixing in a waveguide," *IEEE J. Quantum Electron.*, vol. QE-15, pp. 101-109, 1979.
- [9] C. Karaguleff, G. I. Stegeman, R. Fortenberry, R. Zanon, and G. I. Stegeman, "Degenerate four-wave mixing in planar CS<sub>2</sub> covered waveguides," *Appl. Phys. Lett.*, vol. 46, p. 621, 1985.
- [10] J. M. Nunzi and D. Ricard, "Optical phase conjugation and related experiments with surface plasma waves," *Appl. Phys. A: Solids and Surfaces*, vol. 35, pp. 209-216, 1984.
- [11] G. I. Stegeman, "High speed signal processing with nonlinear integrated optics," *J. Opt. Commun.*, vol. 4, pp. 20-24, 1983.
- [12] E. Weinert-Raczka, "Four wave mixing in a waveguide—Two radiation and two guided modes interaction," *Opt. Commun.*, vol. 49, pp. 245-247, 1984.
- [13] K. Ujihara, "Phase conjugation of a bulk wave by surface plasmons," *J. Opt. Soc. Amer.*, vol. 73, pp. 610-616, 1983.
- [14] C. Karaguleff and G. I. Stegeman, "Degenerate four-wave mixing with surface guided waves," *IEEE J. Quantum Electron.*, vol. QE-20, pp. 716-722, 1984.
- [15] A. Yariv, "Three-dimensional pictorial transmission in optical fibers," *Appl. Phys. Lett.*, vol. 28, pp. 88-89, 1976.
- [16] A. Yariv, J. Au Yeung, D. Fekete, and D. M. Pepper, "Image phase compensation and real-time holography by four-wave mixing in optical fibers," *Appl. Phys. Lett.*, vol. 32, pp. 635-637, 1978.
- [17] R. W. Hellwarth, "Optical beam phase conjugation by four-wave mixing in a waveguide," *Opt. Eng.*, vol. 21, p. 263, 1982.
- [18] J. Au Yeung, D. Fekete, D. M. Pepper, A. Yariv, and R. K. Jain, "Continuous backward-wave generation by degenerate four-wave mixing in optical fibers," *Opt. Lett.*, vol. 4, pp. 42-44, 1979.
- [19] G. J. Dunning and R. C. Lind, "Demonstration of image transmission through fibers by optical phase conjugation," *Opt. Lett.*, vol. 7, pp. 558-560, 1982.
- [20] R. W. Hellwarth, "Theory of phase conjugation by stimulated scattering in a waveguide," *J. Opt. Soc. Amer.*, vol. 68, p. 1050, 1978.
- [21] A. Lattes, C. Gabriel, and H. A. Haus, "Doubly degenerate four-wave mixing in optical waveguides," in *Tech. Dig. Topical Meet. Integrated and Guided Wave Opt.*, Asilomar, CA, Jan. 1982 (Opt. Soc. Amer., Washington, DC, 1982), pp. ThA4-1-ThA4-3.
- [22] K. Ujihara, "Four-wave mixing and two-dimensional phase conjugation of surface plasmons," *Opt. Commun.*, vol. 42, pp. 1-4, 1982.
- [23] —, "Phase conjugation of surface plasmon waves by the third order nonlinearity of a free electron gas," *Opt. Commun.*, vol. 43, pp. 225-228, 1982.
- [24] R. K. Jain and R. C. Lind, "Degenerate four-wave mixing in semiconductor-doped glasses," *J. Opt. Soc. Amer.*, vol. 73, pp. 647-653, 1983.
- [25] S. S. Yao, C. Karaguleff, A. Gabel, R. Fortenberry, C. T. Seaton, and G. I. Stegeman, "Ultrafast carrier and nonlinear grating lifetimes of optical filter glass," *Appl. Phys. Lett.*, vol. 46, pp. 801-802, 1985.
- [26] P. Roussignol, D. Ricard, K. C. Rustagi, and C. Flytzanis, "Optical phase conjugation in semiconductor-doped glasses," *Opt. Commun.*, vol. 55, pp. 143-148, 1985.
- [27] C. N. Ironside, T. J. Cullen, J. F. Duffy, R. H. Hutchins, W. C. Banyai, C. Y. Seaton, and G. I. Stegeman, "Fabrication of integrated nonlinear optical devices," in *Proc. 2nd Conf. Integrated Opt. Eng.*, S. Srinam, Ed., Cambridge, MA, SPIE, vol. 578, 1985, pp. 162-165.
- [28] D. Ricard, Ph. Roussignol, and Chr. Flytzanis, "Surface-mediated enhancement of optical phase conjugation in metal colloids," *Opt. Lett.*, vol. 10, pp. 511-513, 1985.
- [29] G. M. Carter, M. K. Thakur, Y. J. Chen, and J. V. Hryniewicz, "Time and wavelength resolved nonlinear optical spectroscopy of a polydiacetylene in the solid state using picosecond dye laser pulses," *Appl. Phys. Lett.*, vol. 47, pp. 457-459, 1985.

George I. Stegeman, for a photograph and biography, see p. 982 of the June 1986 issue of this JOURNAL.

Colin T. Seaton, for a photograph and a biography, see p. 983 of the June 1986 issue of this JOURNAL.

C. Karaguleff, photograph and biography not available at the time of publication.

# Semiconductor-doped glass ion-exchanged waveguides

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The properties of planar waveguides and directional couplers fabricated by potassium/sodium ion exchange in semiconductor-doped glasses are described.

A new spectrum of ultrafast (picosecond) all-optical devices becomes possible when an optical waveguide contains a medium characterized by an intensity-dependent refractive index.<sup>1</sup> Although many interesting device concepts have been proposed,<sup>1</sup> progress has been hampered by the lack of nonlinear materials with both large nonlinearities and picosecond response times, and from which optical waveguides can easily be fabricated. To date, only a nonlinear coherent coupler, first proposed by Jensen,<sup>2</sup> has been demonstrated with cw excitation in strain-induced waveguides in GaAs/AlGaAs multiple quantum well material.<sup>3,4</sup> This device consisted of two parallel, channel waveguides and, when light is initially inserted into one channel, the transfer efficiency into the second channel depends upon the initial power in the incidence channel. A further refinement is a nonlinear Mach-Zehnder interferometer as described by Lattes *et al.*<sup>5</sup> Recently it has been shown that semiconductor-doped glasses (color filters), which are glasses containing small (10–100 nm) crystallites of  $\text{CdS}_x\text{Se}_{1-x}$ , have usefully large nonlinearities<sup>6,7</sup> ( $n_2 = 10^{-14} \text{ m}^2/\text{W}$ ) for guided wave devices, coupled with picosecond relaxation times<sup>7</sup> ( $\tau < 10^{-11} \text{ s}$ ). For example, the critical power  $P_c$  for a nonlinear coherent coupler<sup>2</sup> acting as an all-optical switch should be approximately 1 W for a channel cross-sectional area of  $10 \mu\text{m}^2$  and a linear transfer length of 5 mm. Since such glasses are relatively inexpensive and can be made with 10% concentrations of sodium, they are promising candidates for waveguide fabrication by ion exchange, one of the more simple waveguide fabrication technologies.<sup>8,9</sup> In this letter we describe the fabrication and the waveguiding characteristics of both planar waveguides<sup>10</sup> and directional couplers in semiconductor-doped glasses.

The color filter glasses used in this study consist of a bulk soda-potash-lime glass matrix doped with small crystallites of the semiconductor compound  $\text{CdS}_x\text{Se}_{1-x}$  with  $x$  chosen to give a red colored glass with a band edge around 590 nm. The nonlinearity is resonant with the band gap and this wavelength is convenient for subsequent characterization of the nonlinear properties of the devices with a mode-locked rhodamine 6G dye laser. The glass content is 9.5% by weight sodium and 3.5% by weight potassium. The substrate index was measured using an Abbe refractometer to be  $1.5185 \pm 0.0001$  at 632.8 nm. Planar waveguides were fabricated by immersing the filter into a bath of molten potassium nitrate at 340 °C (this temperature just above the melting point of 334 °C was found to give the most reproducible re-

sults) in which sodium ions leave the glass to be replaced by potassium ions from the melt. This exchange results in a region of higher refractive index  $\Delta n$  of around 0.009 at the surface which decreases monotonically with depth. To fabricate stripe waveguides, an aluminium diffusion mask is deposited on the glass: the mask has apertures through which selective ion exchange can take place thus defining the waveguide dimensions.

The fabrication of single-mode planar and channel waveguides requires a detailed investigation of the ion-exchange process. A characterization study of  $\text{K}^+/\text{Na}^+$  ion exchange in color filter glass was undertaken similar to those reported in Ref. 8 ( $\text{Ag}^+/\text{Na}^+$  ion exchange) and Ref. 11 ( $\text{K}^+/\text{Na}^+$  ion exchange) for soda-lime microscope slide glass and Ref. 12 ( $\text{K}^+/\text{Na}^+$  ion exchange) for BK-7 glass. A number of planar waveguide samples were prepared in which the diffusion times  $t$  were varied between the range 15 min to 24 h. For every sample the effective index of each mode was determined by the prism coupling method to an accuracy of  $\pm 0.0001$  with a He-Ne laser operating at wavelength of 632.8 nm. The results for both TE and TM polarizations are shown in Fig. 1.

The theoretical dispersion curves which produced an excellent fit to the data were derived as follows. First, the inverse Wentzel-Kramers-Brillouin (WKB) method<sup>13</sup> was used to obtain the mode turning points and also the surface refractive index  $n_s$ , consistently found to be 1.5272 for TE modes and 1.5305 for TM modes. In order to find depth index profiles which accurately fit these points, the finite difference method was used to calculate solutions to the nonlinear diffusion equation in one dimension given by

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} \left( \frac{D_1}{1 - \alpha c} \frac{\partial c}{\partial x} \right), \quad (1a)$$

$$c = c_1/c_0, \quad \alpha = 1 - (D_1/D_0), \quad (1b)$$

where  $c$  is the normalized potassium ion concentration ( $c_1$  being the concentration of the potassium ions and  $c_0$  the total number of diffusing potassium and sodium ions in the glass) and  $D_1$  and  $D_0$  are the self-diffusion constants of the potassium and sodium ions, respectively. The surface concentration ratio was determined by laser induced ion mass analysis (LIMA) of the exchanged glass surface layer to be 9:1  $\text{K}^+/\text{Na}^+$ , giving a boundary condition of  $c = 0.9$ . The refractive index is assumed to vary linearly with the potassium ion concentration. The shape and depth of the index profiles are adjusted by varying the parameters  $\alpha$  and  $D_1$ :

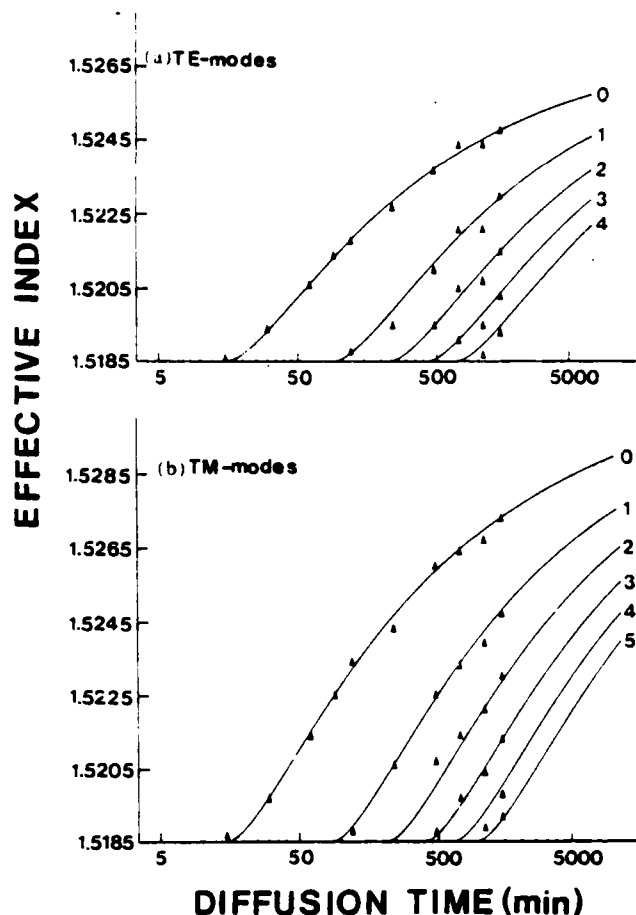


FIG. 1. Theoretical dispersion curves calculated using the Wentzel-Kramers-Brillouin (WKB) method for the optimum index profiles compared to measured mode effective index values for samples fabricated at  $T = 340^\circ\text{C}$ . (a) TE modes and (b) TM modes.

values of  $\alpha = 0.3$  and  $D_1 = 4.95 \times 10^{-16} \text{ m}^2 \text{ s}^{-1}$  were found to give the best least-squares fit for the TE modes, while  $\alpha = 0.3$  and  $D_1 = 4.50 \times 10^{-16} \text{ m}^2 \text{ s}^{-1}$  give the best fit for the TM modes. The apparent anisotropy of ion-exchanged waveguides, as suggested by the discrepancy between the diffusion constants and the surface index values for the TE and TM modes, is thought to be due to stresses introduced into the glass by the different sizes of the two ionic species being exchanged.<sup>13</sup>

Using the best fit refractive index profiles and defining  $d_s$  to be the depth where the index change is equal to  $1/e$  of the surface index change, a linear relationship between  $d_s$  and  $t^{1/2}$  was obtained. From the slope, the "effective" diffusion constant [defined by the relation  $(d_s = (D_e t)^{1/2})$ ] is given by  $D_e = 10.80 \times 10^{-16} \text{ m}^2 \text{ s}^{-1}$  for TE modes and  $D_e = 9.32 \times 10^{-16} \text{ m}^2 \text{ s}^{-1}$  for TM modes. Finally, the WKB method was employed using the diffusion parameters obtained above to calculate the curves fitted to the data in Fig. 1. The excellent fit indicates that the refractive index profiles and the  $D_e$  values determined are reasonably accurate. This agreement is particularly important for predicting the short diffusion times required for single-mode waveguides. A diffusion time of 1 h was chosen from these results as the optimum time for the fabrication of single-mode waveguides.

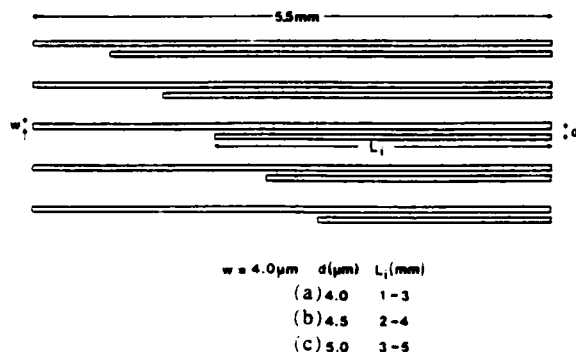


FIG. 2. Schematic diagram of directional coupler pattern used to fabricate devices. This pattern was repeated three times on the mask for different waveguide separations ( $d$ ) of (a) 4.0, (b) 4.5, and (c) 5.0  $\mu\text{m}$ . The interaction length was varied in steps of 0.5 mm over the ranges of (a) 1.0–3.00 mm, (b) 2.0–4.0 mm, and (c) 3.0–5.0 mm. The waveguide width ( $w$ ) was nominally 4.0  $\mu\text{m}$  for all the couplers on the mask.

The theoretical effective index values of stripe waveguides and the transfer length for directional couplers were calculated using the numerical model derived by Walker *et al.*<sup>9</sup> First, the model is used to solve the nonlinear diffusion equation in two dimensions to give the refractive index profile  $n(x, y)$ , then the Helmholtz wave equation is solved for such a region using the variational method (the model is restricted to quasi-TE modes) to give the mode effective index values.

For a diffusion time of 1 h at  $340^\circ\text{C}$  the slab effective index is 1.5205. The theory predicts that stripe waveguides formed with the same diffusion parameters will be single mode for aperture widths  $w$  of 3–5  $\mu\text{m}$  with effective index values from 1.5189 to 1.5196. The mask design used to experimentally verify directional coupler calculations is shown in Fig. 2.

Several samples were fabricated using this mask and the edges polished to facilitate end-fire coupling (this process removed 0.5 mm from the interaction length of each device). Light from a He-Ne laser was coupled in turn into each de-

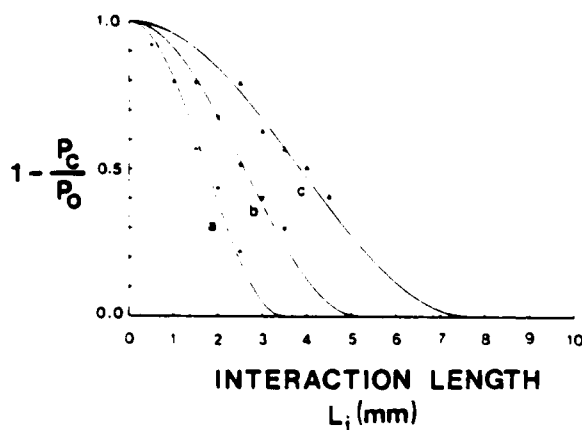


FIG. 3. Plot of the measured normalized coupled power ( $1 - P_c/P_0$ ) vs. interaction length ( $L_i$ ) for the three sets of similar couplers on a sample. The best fit  $\cos^2(\pi z/2L_c)$  curves are also shown. The results are shown in Table I. (The lengths are 0.5 mm less than the lengths in Fig. 2 because this amount is lost in the polishing process.)

TABLE I. Comparison of theoretical and measured coupler transfer length for devices prepared at  $T = 340^\circ\text{C}$  for 1 h.

Coupler set	Waveguide width $w$ ( $\mu\text{m}$ )	Waveguide separation $d$ ( $\mu\text{m}$ )	Transfer length $L_c$ (mm)	
			measured	theoretical
a	4.2	4.2	$3.5 \pm 0.25$	3.5
b	4.2	4.6	$5.2 \pm 0.25$	5.5
c	4.2	5.3	$7.7 \pm 0.35$	7.9

All guide widths and separations measured to an accuracy of  $\pm 0.1 \mu\text{m}$ .

vice on a sample at the single-guide end and the power in each of the output guides was determined by focusing the near-field image onto the camera of a calibrated vidicon system. Figure 3 shows the power remaining in the input guide versus the device interaction length for the three sets of devices. The best fit  $\cos^2(\pi z/2L_c)$  curves are also shown to estimate the coupling length. Table I gives the actual device parameters and measured transfer lengths compared with the predicted transfer lengths calculated from the theoretical model. Very good agreement was obtained.

In summary, good quality single-mode directional couplers can be made by  $\text{K}^+/\text{Na}^+$  ion exchange in semiconductor-doped glasses. The waveguiding properties of a directional coupler can also be predicted with the model presented here. Experiments are currently under way to measure the nonlinear properties of the directional couplers, as well as the Mach-Zehnder devices.

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<sup>1</sup>Recently reviewed in G. I. Stegeman and C. T. Seaton, *Appl. Phys. Rev.* (in *J. Appl. Phys.*) **58**, R57 (1985).

<sup>2</sup>S. M. Jensen, *IEEE J. Quantum Electron.* **QE-18**, 1580 (1982).

<sup>3</sup>P. Li Kam Wa, J. E. Sitch, N. J. Mason, J. S. Roberts, and P. N. Robson, *Electron. Lett.* **21**, 26 (1985).

<sup>4</sup>P. Li Kam Wa, J. H. Marsh, P. N. Robson, J. S. Roberts, and N. J. Mason, *Proceedings of the 2nd Conference on Integrated Optical Engineering*, Cambridge, SPIE (The Society of Photo-Optical Instrumentation Engineers), edited by S. Siram, **578**, 110 (1985).

<sup>5</sup>A. Lattes, H. A. Haus, F. J. Leonberger, and E. P. Ippen, *IEEE J. Quantum Electron.* **QE-19**, 1718 (1983).

<sup>6</sup>R. K. Jain and R. C. Lind, *J. Opt. Soc. Am.* **73**, 647 (1983).

<sup>7</sup>S. S. Yao, C. Karaguleff, A. Gabel, R. Fortenberry, C. T. Seaton, and G. I. Stegeman, *Appl. Phys. Lett.* **46**, 801 (1985).

<sup>8</sup>G. Stewart, C. A. Millar, P. J. R. Laybourn, C. D. W. Wilkinson, and R. M. De La Rue, *IEEE J. Quantum Electron.* **QE-13**, 192 (1978).

<sup>9</sup>R. G. Walker, C. D. W. Wilkinson, and J. A. H. Wilkinson, *Appl. Opt.* **22**, 1923 (1983).

<sup>10</sup>C. N. Ironside, J. F. Duffy, R. H. Hutchins, W. C. Banyai, C. T. Seaton, and G. I. Stegeman, *Technical Digest of the 5th International Conference on Integrated Optics and Optical Communications and of the 11th European Conference on Optical Communications*, Venice, Italy, 1985, p. 237.

<sup>11</sup>G. L. Yip and J. Albert, *Opt. Lett.* **10**, 151 (1985).

<sup>12</sup>J. E. Gortych and D. G. Hall, *Opt. Lett.* **11**, 100 (1986).

<sup>13</sup>J. Finak, H. Jerominek, Z. Opilski, and K. Woitalla, *Opt. Appl.* **XII**, 11 (1982).

# Gaussian beam excitation of $TE_0$ nonlinear guided waves

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Selective, efficient excitation of  $TE_0$  nonlinear guided waves is demonstrated numerically. For a thin film bounded by two self-focusing media, three different field distributions corresponding to the same flux level can be excited independently by suitable Gaussian input beams.

To date several integrated optics devices have been proposed utilizing nonlinear waveguides (NLWG's), for example, upper and lower threshold devices, nonlinear couplers, optical switches, etc.<sup>1</sup> Such proposals have invariably been based on the NLGW dispersion curves (guided wave flux versus effective index)<sup>2</sup> even in the absence of data on the stability of the various branches and of the possibility of externally exciting the NLGW's. Moloney *et al.*<sup>3,4</sup> and Jones and Moloney<sup>5</sup> have recently addressed the stability question both numerically and analytically, and a comprehensive picture is now emerging. In contrast, the problem of external excitation of NLGW's (in the waveguide context) has not been discussed so far, and is the subject of this letter. Specifically, we show that, for a fixed input flux, selective excitation of the corresponding  $TE_0$  NLGW's by end firing of appropriately tailored Gaussian beams is indeed possible. Implications for device design concepts are also discussed.

We treat the case of TE waves of frequency  $\omega$  in a planar NLGW as shown in Fig. 1. For this preliminary study the electric field is assumed homogeneous in the  $y$  direction. Then writing the electric field as

$$E(r,t) = \frac{1}{2} y [W(x,z)e^{i(\beta z - \omega t)} + \text{c.c.}] \quad (1)$$

gives in the usual slowly varying envelope approximation,

$$2i\beta \frac{\partial W}{\partial z} + \frac{\partial^2 W}{\partial x^2} - [\beta^2 - n^2(x, |W|^2)]W = 0, \quad (2)$$

where the refractive index in the various media is described by

$$n^2(x, |W|^2) = n_c^2 + \alpha_c |W(x,z)|^2, \quad \gamma = c, f, s, \quad (3)$$

and the subscripts  $c$ ,  $f$ ,  $s$  refer to the cladding ( $x < -d$ ), film ( $-d < x < d$ ), and substrate ( $x > d$ ), respectively. Here the coordinates  $x$  and  $z$ , and  $d$  are in units of  $k_0^{-1} = c/\omega$ . The NLGW's of the system are solutions of Eq. (2) such that  $W(x,z) = W_0(x)$ . Equation (2) along with the boundary conditions of continuity of  $W$  and  $\partial W/\partial x$  at the interfaces ( $x = \pm d$ ) can then be used to generate the dispersion curves for the system. Note that due to the nonlinearity assumed in this problem, several NLGW solutions may exist for a given  $\beta$ .<sup>1,2</sup> An example of the dispersion curves for the  $TE_0$  NLGW's of a waveguide with nonlinear cladding and substrate, and a linear film, is shown in Fig. 2 (we use the parameter values given in this figure throughout). We choose self-focusing nonlinearities since this case contains by far the richest set of new phenomena.<sup>1,2</sup> The regions marked by the dashed lines are unstable under propagation,

and the remaining regions are stable and are labeled I, II, and III, respectively.<sup>3</sup> The inset beside each stable region indicates the field distribution of the NLGW on that branch. For example, in region II the NLGW is associated with self-focusing in the medium with the lower nonlinear coefficient, whereas in III it is associated mainly with self-focusing in the other bounding medium. At high flux levels these solutions degenerate into nonlinear surface polaritons at their respective interfaces, each independent of the other interface.

To investigate the excitation of NLGW's we have solved Eq. (2) with initial data corresponding to a collimated Gaussian input beam:

$$W_{in}(x) = W_N e^{-(x-x_0)^2/w_0^2}, \quad (4)$$

where  $W_N$  is used to adjust the input beam flux,  $x_0$  is the displacement of the beam center from the guide center, and  $w_0$  is the Gaussian spot size. This boundary condition corresponds to end firing a Gaussian beam onto the NLGW. Note that we ignore any nonlinear reflection that may occur at the air-waveguide interface. This is valid since the input beam is incident normally onto the interface whereas nonlinear effects occur only for angles close to the critical angle for total internal reflection.<sup>6,7</sup>

For our numerical experiment we have fixed the input flux ( $S_{in} = 0.165$ ), and as indicated by the horizontal line in Fig. 2, there are three distinct, stable NLGW solutions. For each solution we examined the NLGW profile and estimated values for  $x_0$  and  $w_0$  such that the input Gaussian would resemble the corresponding NLGW. For example, for the

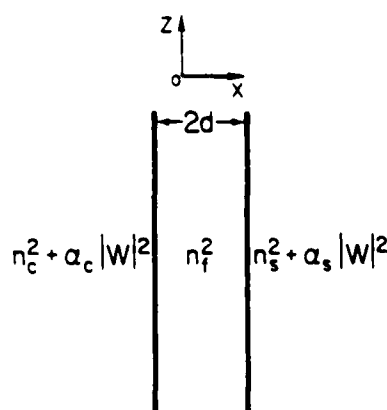


FIG. 1. Nonlinear waveguide geometry. a linear thin film of thickness  $2d$  is bounded by two self-focusing nonlinear media.

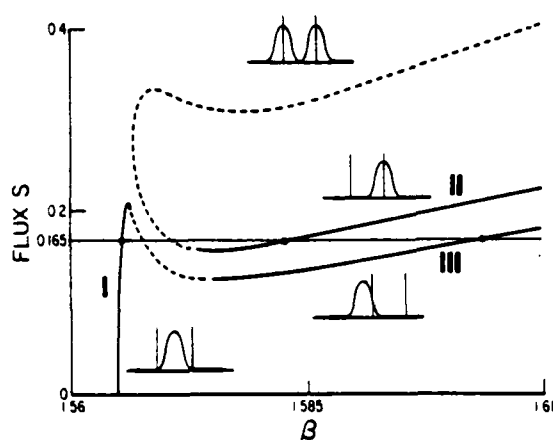


FIG. 2. Guided wave flux ( $S$ ) vs effective index ( $\beta$ ) for two self-focusing bounding media. The solid and dashed lines indicate stable and unstable regions, respectively, and the insets show the nature of the NLGW's on the various branches. Parameter values are  $n_c = n_r = 1.55$ ,  $n_f = 1.57$ ,  $\alpha_c = 10^{-2}$ ,  $\alpha_r = 8 \times 10^{-3}$ ,  $\alpha_f = 0$ , and  $d = 8$ .

solution on branch I of Fig. 2 we chose  $\omega_0 = 10.0$  and  $x_0 = 0.0$ , whereas for branch II we have  $\omega_0 = 6.0$  and  $x_0 = 10.3$ . The evolution of the Gaussians for branches I–III are shown in Figs. 3(a)–3(c), respectively. In all cases the Gaussians evolve toward the NLGW they were tailored to excite. This was verified by detailed examination of the final beam profile and the corresponding NLGW. We have therefore demonstrated that selective excitation of the  $TE_0$  NLGW's at a fixed flux level using a Gaussian beam is possible. These results indirectly imply that selective excitation is

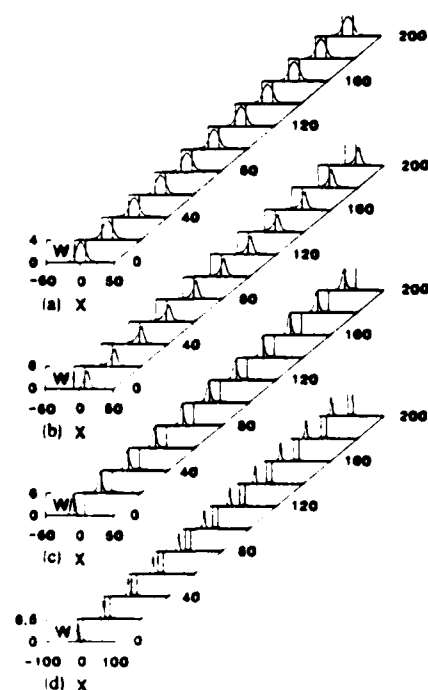


FIG. 3. Evolution of Gaussian input beams for  $S_{in} = 0.165$  and (a)  $x_0 = 0$ ,  $\omega_0 = 10.0$ ; (b)  $x_0 = 10.3$ ,  $\omega_0 = 6.0$ ; (c)  $x_0 = -10.6$ ,  $\omega_0 = 4.0$ ; (d)  $x_0 = -9.0$ ,  $\omega_0 = 4.0$ . The propagation coordinate is in units of free-space wavelengths, and the vertical lines are the waveguide boundaries.

also possible if only the cladding is nonlinear; in that case the only difference is that branch II vanishes and there are only two NLGW's. We have furthermore verified numerically that Gaussian beam excitation is possible for many values of the ratio  $\alpha_c/\alpha_r$ . The results presented here are representative of our general findings.

A new question immediately arises from these results, namely, how sensitive is the coupling to the initial Gaussian beam profile? First, we stress that our estimates for  $z_0$  and  $\omega_0$  came from visual examination of the NLGW's which indicates that there is no exceptional sensitivity to initial conditions. However, if the input beam profile is too different from a NLGW it decays mainly via emission of radiation and/or a soliton which is ejected into the nonlinear medium with the larger nonlinear coefficient.<sup>4</sup> (If both media are identical, two solitons are emitted, one into each medium.) An example of the soliton decay is shown in Fig. 3(d) which corresponds to the situation in Fig. 3(c) but with the beam center misaligned from  $x_0 = -10.6$  to  $x_0 = -9.0$ . More details of these decay processes will be published elsewhere.

These results show that the input beam profile is a significant control parameter in considerations of NLGW excitation. The input flux alone is not sufficient to characterize the input. This has implications for device design concepts. For example, previous proposals for optical power limiting using NLGW's have relied on the fact that for certain configurations (e.g., a waveguide with a self-defocusing cladding which starts above cutoff), there exist no NLGW's above a certain critical flux.<sup>1</sup> For the case shown in Fig. 2, we can couple a Gaussian beam ( $x_0 = 0.0$ ,  $\omega_0 = 10.0$ ) into branch I very efficiently. (The system is essentially linear on this branch.) However, for input fluxes above which this branch does not exist, our input beam does not match the solutions on the two remaining branches (II and III) and the input decays via emission of radiation and/or solitons, leaving a NLGW on branch I of reduced flux. This process produces threshold behavior and optical limiting. Without proper consideration of the input profile, this action cannot be understood since NLGW's exist for all possible input fluxes.

In conclusion, we have demonstrated that selective excitation of stable  $TE_0$  NLGW's using a Gaussian input beam is possible. Indeed it seems that simply matching the input beam to a particular NLGW is sufficient to guarantee selective excitation.

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<sup>1</sup>C. T. Seaton, G. I. Stegeman, and H. G. Winful, *Opt. Eng.* **24**, 593 (1985).

<sup>2</sup>C. T. Seaton, J. D. Valera, R. L. Shoemaker, G. I. Stegeman, J. Chilwell, and S. D. Smith, *IEEE J. Quantum Electron.* **QE-21**, 774 (1985).

<sup>3</sup>J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, *Appl. Phys. Lett.* **48**, 826 (1986).

<sup>4</sup>J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, *Opt. Lett.* **11**, 315 (1986).

<sup>5</sup>C. K. R. T. Jones and J. V. Moloney (unpublished).

<sup>6</sup>W. J. Tomlinson, J. P. Gordon, P. W. Smith, and A. E. Kaplan, *Appl. Opt.* **21**, 2041 (1982).

<sup>7</sup>P. W. Smith and W. J. Tomlinson, *IEEE J. Quantum Electron.* **QE-20**, 30 (1984) and references therein.

## Multisoliton emission from a nonlinear waveguide

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We demonstrate numerically that external excitation of a nonlinear waveguide can produce sequential threshold behavior via multisoliton emission from the waveguide. This behavior is similar to that predicted to occur at a nonlinear interface.

Following the pioneering work of Kaplan<sup>1</sup> on the reflection of a plane wave from a linear-nonlinear interface, several papers appeared on this subject.<sup>2-9</sup> This interest stemmed from the possibility of bistable reflection from such an interface.<sup>1</sup> Although it is now generally accepted that bistable reflection is not possible (as opposed to a hysteretic response) several of the results from the theoretical studies, such as the nonlinear Goos-Hänchen<sup>7,9</sup> effect and the transmission of self-focused channels (or solitons) through the interface,<sup>2,7</sup> are of interest in their own right. To the best of our knowledge only the former effect has received further attention.

In this Brief Report we consider the external excitation of a nonlinear waveguide (NLWG) where the film and substrate are linear but the cladding displays a nonlinear refractive index (optical Kerr effect). Intuitively one may expect that effects reminiscent of the nonlinear interface problem can arise since the NLWG comprises at least one such interface. Here we report results showing the transmission of solitons through the film-cladding interface, the number and angle of emission of which depends on the input flux. [The input beam profile is held fixed as the zeroth-order transverse-electric (TE) mode of the linear guide.] The flux trapped in the waveguide then shows sequential threshold behavior as a function of the input flux as a result of this multisoliton emission. An intuitive explanation for the thresholds utilizing the NLWG dispersion curve for the system is given. We remark that the emission of a soliton from a NLWG has previously been reported as a route by which unstable nonlinear guided waves (NLGW's) decay.<sup>10</sup> However, in that case the input flux fixes the input beam profile whereas here we hold the input profile fixed which is more in line with experimental procedures. Potential applications of this effect include optical limiting, coupling of adjacent waveguides in the absence of evanescent field overlap, and a light-driven angular scanning element.

We consider TE waves of frequency  $\omega$  in a slab waveguide, then assuming that the electric field is homogeneous in the  $y$  direction ( $z$  and  $x$  being the propagation

and transverse coordinates in units of  $c/\omega$ ) and writing the field as

$$E(\mathbf{r}, t) = \frac{1}{2} y [W(x, z) e^{i(\beta z - \omega t)} + \text{c.c.}] \quad (1)$$

yields the usual slowly varying envelope equation for  $W(x, z)$ :<sup>11</sup>

$$2i\beta \frac{\partial W}{\partial z} + \frac{\partial^2 W}{\partial x^2} - [\beta^2 - n^2(x, |W|^2)]W = 0. \quad (2)$$

Here the refractive index in the various media is given by

$$n^2(x, |W|^2) = n_\gamma^2 + \alpha_\gamma |W(x, z)|^2, \quad \gamma = c, f, s \quad (3)$$

the subscripts  $c, f, s$  referring to the cladding ( $x \leq -d$ ), film ( $-d \leq x \leq d$ ), and substrate ( $x \geq d$ ), respectively. For the results presented here we specifically set  $n_c = n_s = 1.55$ ,  $n_f = 1.57$ ,  $\alpha_c = 10^{-2}$ , and  $\alpha_f = \alpha_s = 0$ , which corresponds to a self-focusing Kerr-type nonlinear cladding.

The NLGW's are found as the solutions of Eq. (2) such that  $W(x, z) = W_0(x)$ :<sup>12</sup> Equation (2) along with the continuity conditions on the tangential components of the electric and magnetic fields can then be used to generate the dispersion curves (guided wave flux  $S$  versus effective index  $\beta$ ) for the system. In Fig. 1(a) we show the dispersion curve for the TE<sub>0</sub> NLGW's of a NLWG described by the parameters given above (note that since there is only one nonlinear medium the NLGW is uniquely specified by  $\beta$ ). For this particular configuration the negative-slope region of the dispersion curve is unstable under propagation and is indicated by a dashed line, the regions marked I and II are stable.<sup>11</sup> The inset beside each branch shows the general nature of the solution on that branch (e.g., on branch II the solution is concentrated around the film-cladding interface<sup>12</sup>), and the critical flux  $S_c$  is that flux above which the NLGW's on branch I cease to exist (for the example here  $S_c \approx 0.195$ ).

Our numerical experiment consisted of launching an input beam of fixed profile but variable flux onto the



Some features of this soliton emission draw attention. Firstly and perhaps most importantly, the first threshold provides a highly desirable optical limiter characteristic: the input-output transfer is essentially 100% right up to this point at which the output drops drastically. Presumably the switch contrast shown in Fig. 1(b) could be further increased by varying the guide parameters. Furthermore, the output, which is always a branch-I NLGW and closely resembles the linear  $TE_0$  mode of the waveguide, is collimated. Thus, in contrast to previous proposals for optical limiters based on nonlinear refractive effects,<sup>15-17</sup> the present system does not impose any undesirable phase-curvature on the output beam. Secondly, the angle of emission of the solitons is a function of the input flux. This effect was also observed by Tomlinson *et al.*<sup>7</sup> in their study of nonlinear interfaces. As pointed out by these authors, this effect has potential use as a light-driven angular scanning element. Finally, we have found that a soliton emitted from one NLGW can be at least

partially trapped by a second adjacent guide. This offers the possibility of directional-coupler action without the need for evanescent field overlap of the guides. Furthermore, since soliton emission occurs only above a given threshold flux, coupling between the guides will experience the same threshold behavior which could be used to construct logic elements.

In conclusion, we have shown that external excitation of a NLGW can produce sequential threshold behavior through multisoliton emission, and a simple explanation for the threshold behavior has been advanced based on the NLGW dispersion curves.

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<sup>1</sup>A. E. Kaplan, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 132 (1976) [JETP Lett. **24**, 114 (1976)]; Zh. Eksp. Teor. Fiz. **72**, 1710 (1977) [Sov. Phys.—JETP **45**, 896 (1977)].

<sup>2</sup>N. N. Rosanov, Opt. Spektrosk. **47**, 606 (1979) [Opt. Spectrosc. (USSR) **47**, 335 (1979)].

<sup>3</sup>P. W. Smith, J. P. Hermann, W. J. Tomlinson, and P. J. Maloney, Appl. Phys. Lett. **35**, 846 (1979).

<sup>4</sup>D. Marcuse, Appl. Opt. **19**, 3130 (1980).

<sup>5</sup>W. J. Tomlinson, Opt. Lett. **5**, 323 (1980).

<sup>6</sup>P. W. Smith, W. J. Tomlinson, P. J. Maloney, and J. P. Hermann, IEEE J. Quantum Electron. **QE-17**, 340 (1981).

<sup>7</sup>W. J. Tomlinson, J. P. Gordon, P. W. Smith, and A. E. Kaplan, App. Opt. **21**, 2041 (1982).

<sup>8</sup>P. W. Smith and W. J. Tomlinson, IEEE J. Quantum Electron. **QE-20**, 30 (1984).

<sup>9</sup>N. N. Akhmediev, V. I. Korneev, and Yu. V. Kuz'menko, Zh. Eksp. Teor. Fiz. **88**, 107 (1985) [Sov. Phys.—JETP **61**, 62 (1985)].

<sup>10</sup>J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman,

Opt. Lett. **11**, 315 (1986).

<sup>11</sup>J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, Appl. Phys. Lett. **48**, 826 (1986).

<sup>12</sup>C. T. Seaton, J. D. Valera, R. L. Shoemaker, G. I. Stegeman, J. Chilwell, and S. D. Smith, J. Quantum Electron. **QE-21**, 774 (1985).

<sup>13</sup>H. Vach, C. T. Seaton, G. I. Stegeman, and I. C. Khoo, Opt. Lett. **9**, 238 (1984).

<sup>14</sup>We have shown that in order to selectively excite the NLGW's one must tailor the input beam to match that solution; failure to do so leads to decay of the input field: E. M. Wright, G. I. Stegeman, C. T. Seaton, and J. V. Moloney, Appl. Phys. Lett. **49**, 435 (1986).

<sup>15</sup>J. A. Hermann and M. E. Grigg, Opt. Commun. **49**, 367 (1984).

<sup>16</sup>J. A. Hermann, J. Opt. Soc. Am. B **1**, 729 (1984).

<sup>17</sup>E. W. Van Stryland, H. Vanherzeele, M. A. Woodall, M. J. Soileau, A. L. Smirl, S. Guha, and T. F. Boggess, Opt. Eng. **24**, 613 (1985).

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